Using Micro Computed Tomography to Better Characterize the Apollo Sample Suite: a Retroactive PET Style Analysis.

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Motivation

- The overarching goal of this presentation is to show that the micro-CT technique is a useful tool in the curation of Apollo samples.
  - Most of what I will show here is applicable to other astromaterials collections at JSC (esp. meteorites)
- Ultimately we used this as the justification for adding micro-CT as part of the core capabilities of JSC curation.
- Part of our larger plan to modernize the curation process for Apollo (and all other) samples, using non- (or minimally) invasive techniques to improve the curation process.
  - Would include other techniques in the future, e.g., micro-XRF, scanning Raman, FTIR, 3-D scanning and imaging, etc.

More Motivation

- The Apollo sample collection is a "mature" collection
  - Most of the large samples have been well studied, though new advances are still being made with them.
- PIs continue to clamor for new samples to study
  - Plutonic samples to nail down the timing of the formation and evolution of the Moon.
  - Evolved lithologies to constrain how the lunar crust evolved.
  - Better understand the volatile budget of the Moon
- Terrestrial weathering in lunar meteorites limits their usefulness for some things.
- The key to giving PIs what they want can be found in clasts in polymict Apollo breccias
  - We need to characterize these while preserving their pristinity

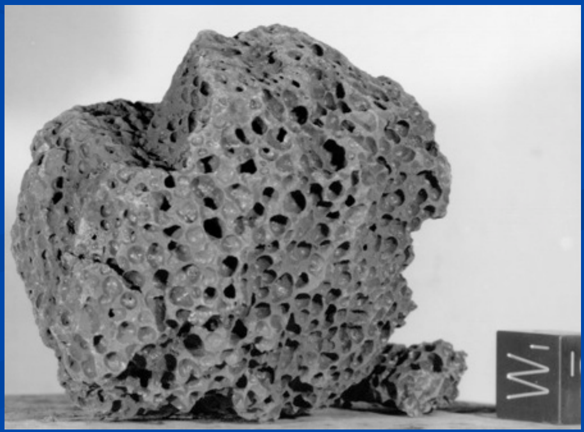
Apollo Sample Suite

- From 1969-1972 the Apollo astronauts collected 382 kg of rocks, soils, and cores from 6 locations on the Moon.
- They are the only astro-material samples collected with geologic context, which increases their usefulness.
- Studies of the large igneous rocks from the Moon shaped (and continue to shape) our understanding of lunar formation and evolution.

76535
Troctolite
Mg-Suite

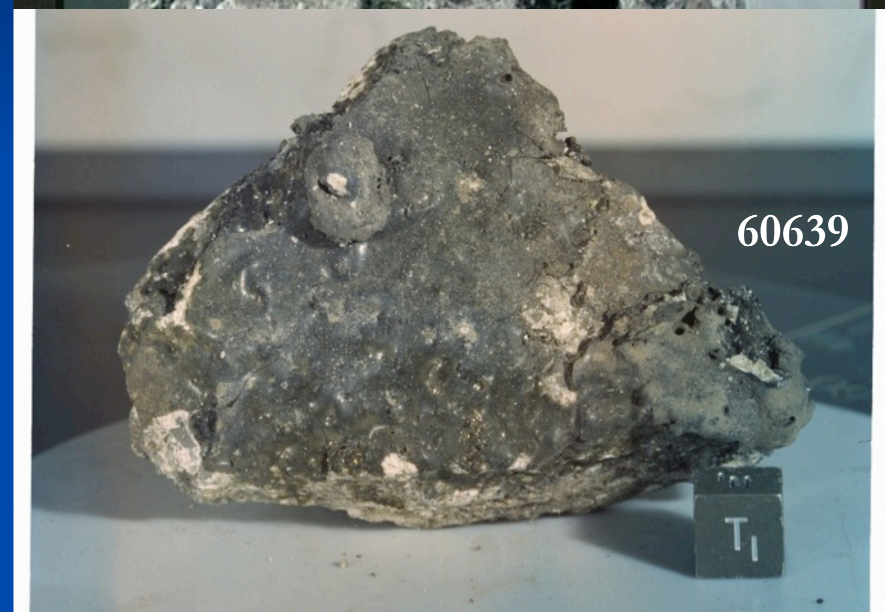
62275 - FAN

15556
Low-Ti
Basalt



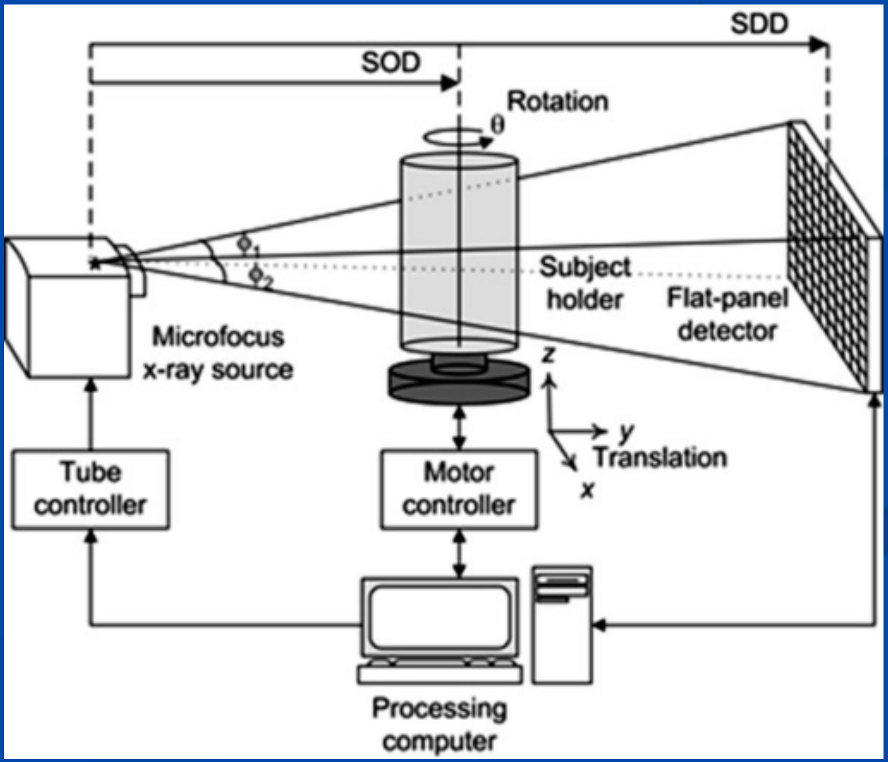
Apollo Sample Suite

- The majority of Apollo rock samples returned are in fact polymict breccias.
  - If we exclude basalts it is an overwhelming majority.
- These contain thousands of small (mm to cm) sized clasts.
  - Modern analytical techniques have reduced the mass needed for analyses.
- Unambiguously identifying the lithology of a clast using optical microscopy is challenging.
- Many polymict breccias are glass coated, further obfuscating classification of clasts.



Micro-CT – The Basics

- High energy (up to ~450 kV, 100-200 kV typical for hard rock scans) x-ray beam is projected through a sample.
  - Uses a micro-focus x-ray source (typically 1-5 μm)
- The attenuation of the X-ray cone is recorded on a detector in 2-D slices
  - Many 2-D slices are acquired as the sample is rotated by fractions of a degree (>1000)
  - The resolution of the scan is related to the size of the sample and the detector.
- Computer software is used to reconstruct these 2-d slices into 3-d volumes.



Our Analyses

- We've scanned 10 samples at the Natural History Museum, London
  - 10057,19 – Mare Basalt, 132 g
  - 14305,483 – Regolith Breccias, 155 g
  - 14321,1404 – Regolith Breccia, 346 g
  - 15205,0 – Regolith Breccia, 136 g
  - 15405,0 – Impact Melt Breccia, 201 g
  - 60639,0 – Regolith Breccia, 153 g
  - 15555,62 + ,1039 – Mare Basalt, 33/66 g
  - 15556,111 +, 215 – Mare Basalt, 44/354 g
  - 60015,180 – Ferroan Anorthosite, 122 g
  - 70017,72 – Mare Basalt, 127 g
- Scans were made at 205-220 kV, 135-160 μA, and 20-40 μm/voxel

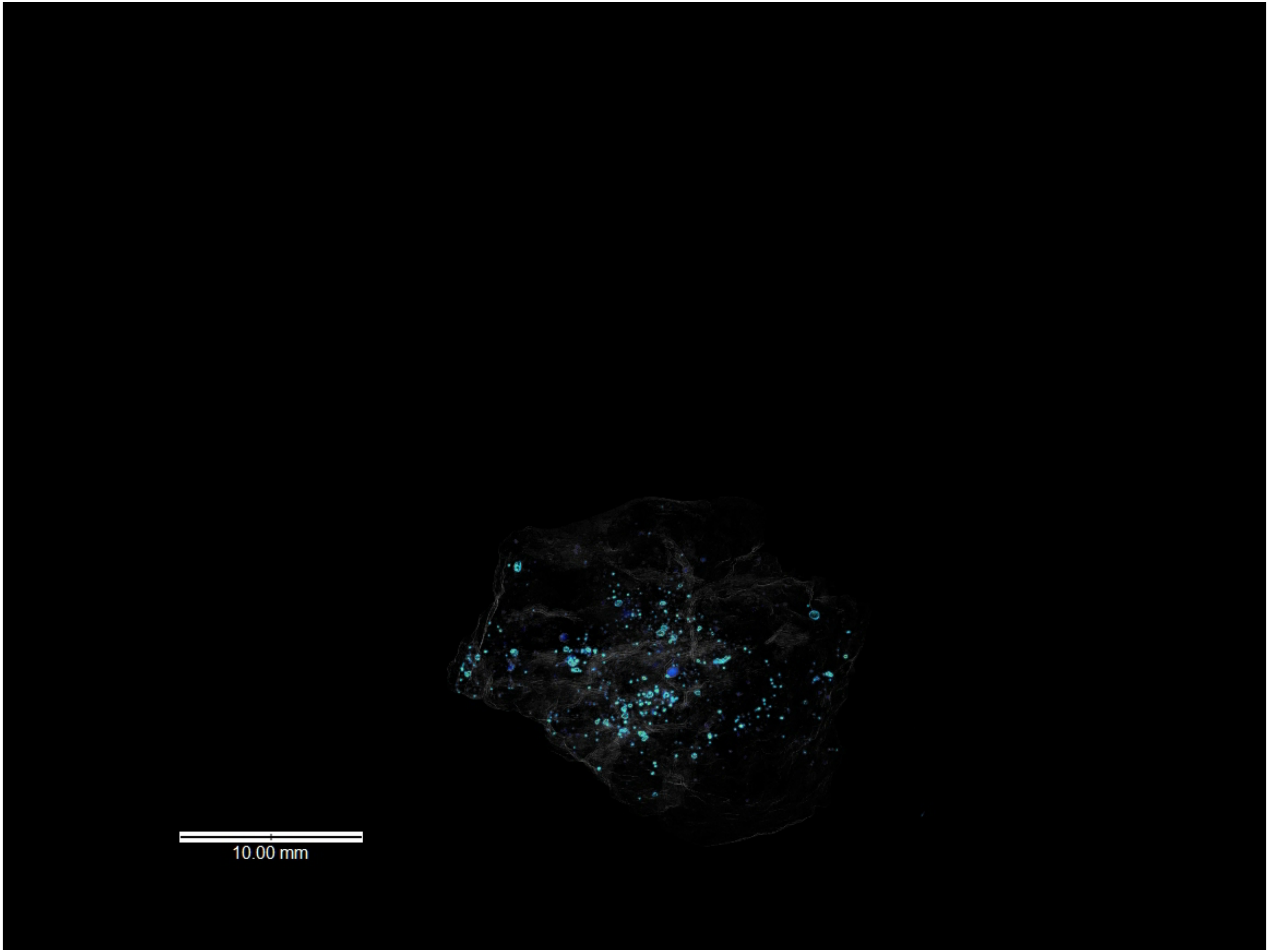
Special thank you to Univ. of Texas CT facility as well.

Nikon X-Tek HMXST 225 system at NHM - London

14321 sample triple bagged in Teflon and immobilized in a cardboard tube

Scan of 60639

- Apollo 16 regolith breccia 60639 is a fairly generic Apollo 16 regolith breccia, with one important caveat:
  - It is the only Apollo 16 sample containing a sizable basalt clast, which is the only mid-TiO_2 basalt on the Moon (6 wt% TiO_2).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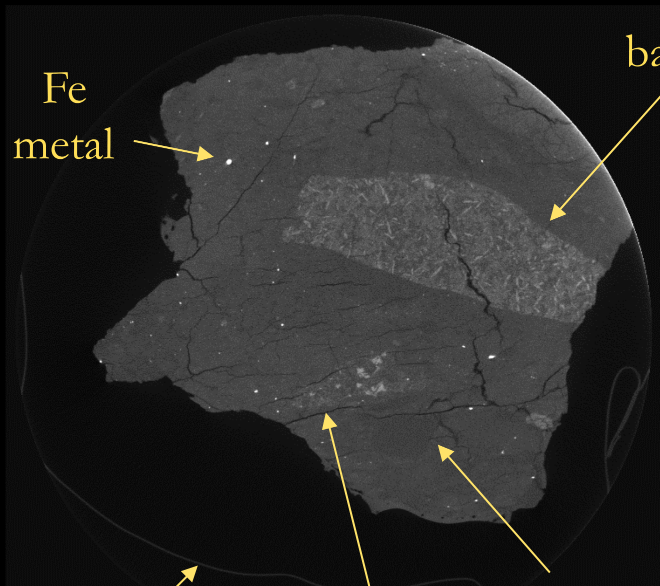
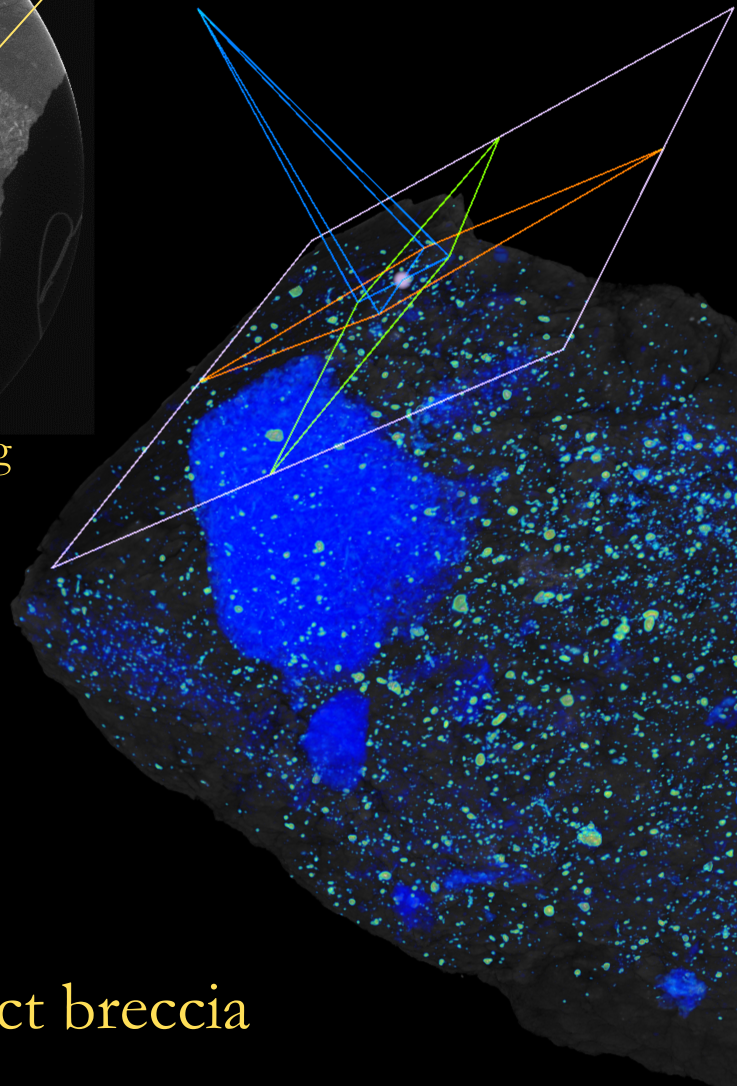
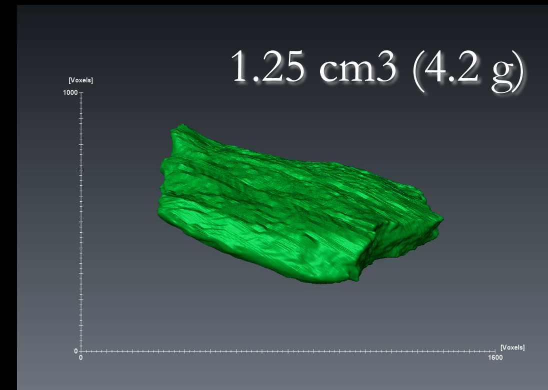


Subvolume scan –
20 μm resolution





Basalt clast
segmented out

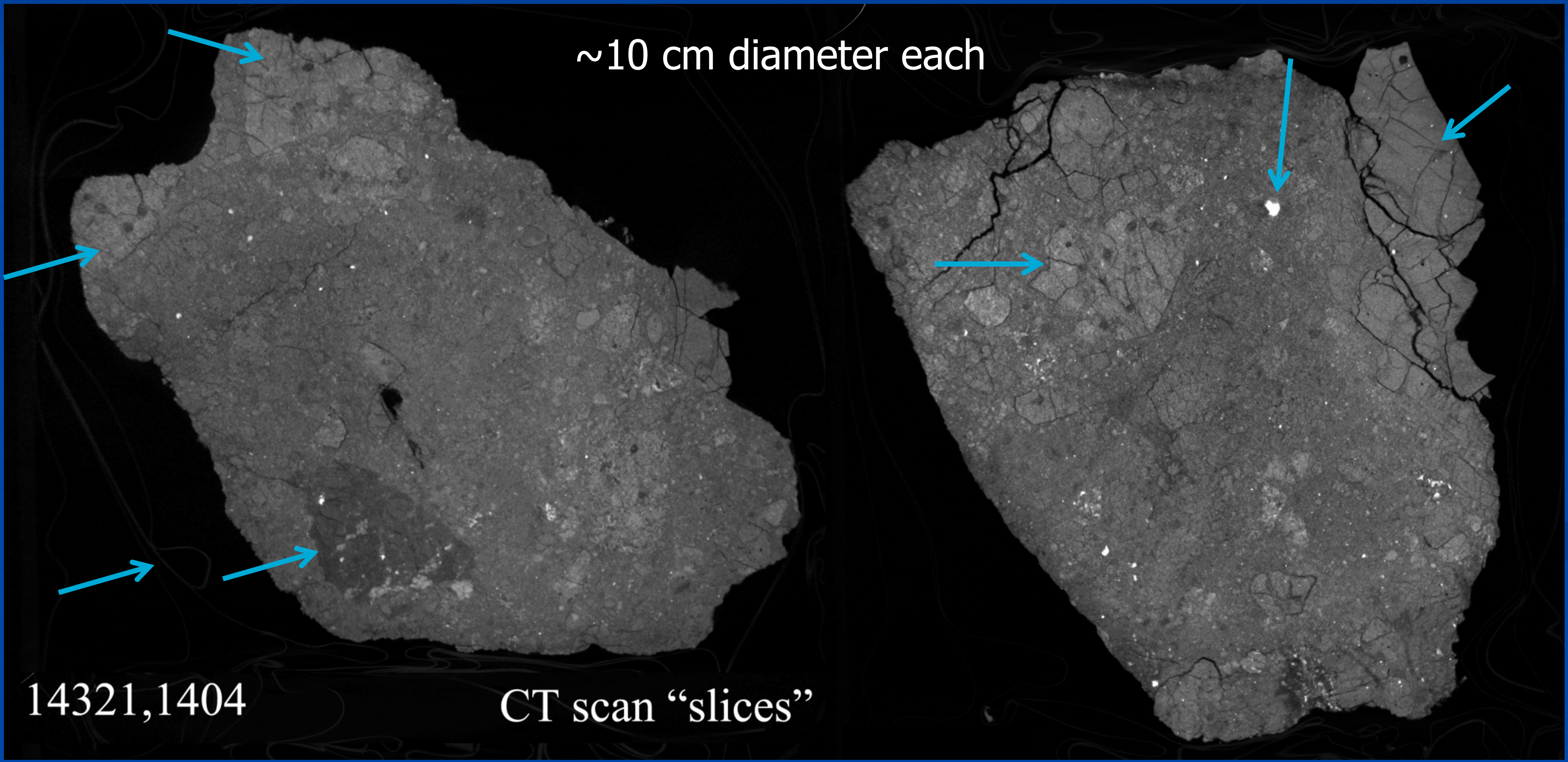
60639,0
Apollo 16 polymict breccia

View of the clasts within the sample.

Micro-CT scan at
215 kV, 160 μA, 3100 scans

Scan of 14321

- Apollo 14 regolith breccia 14321 was the largest Apollo 14 sample (> 9 kg) containing important clast types
  - These include troctolites, high-Al and high-K basalt clasts, as well as a variety of evolved clasts such as granites and alkali anorthosites.



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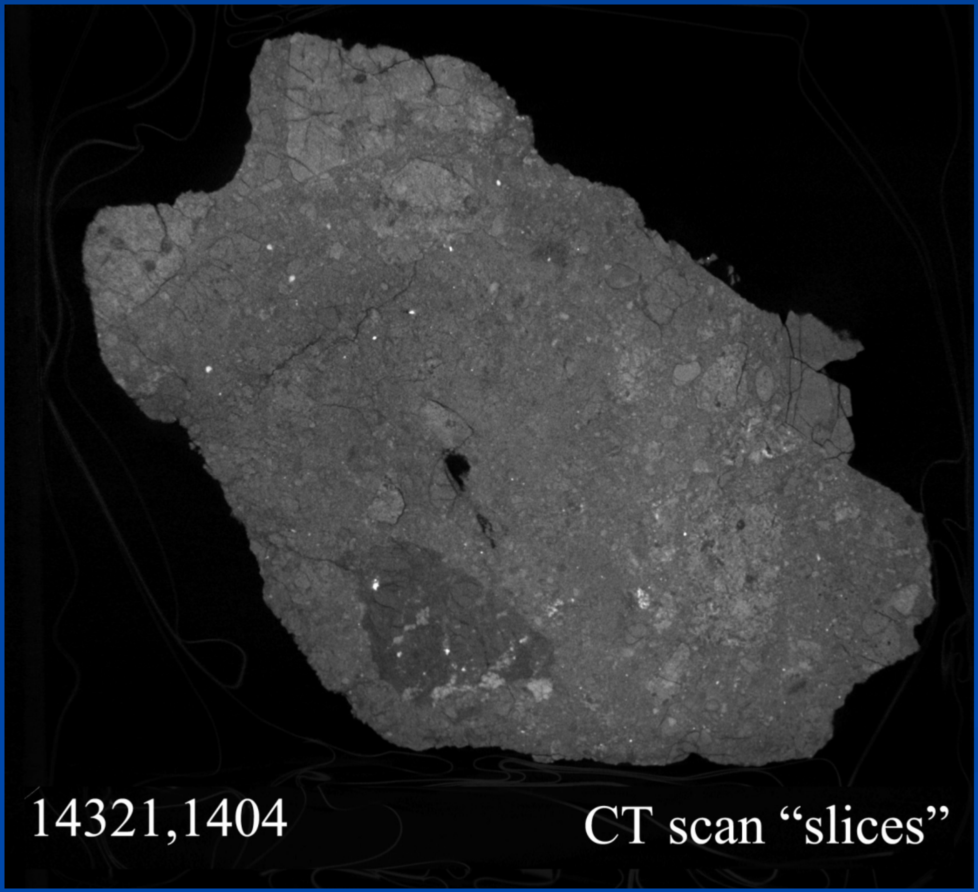
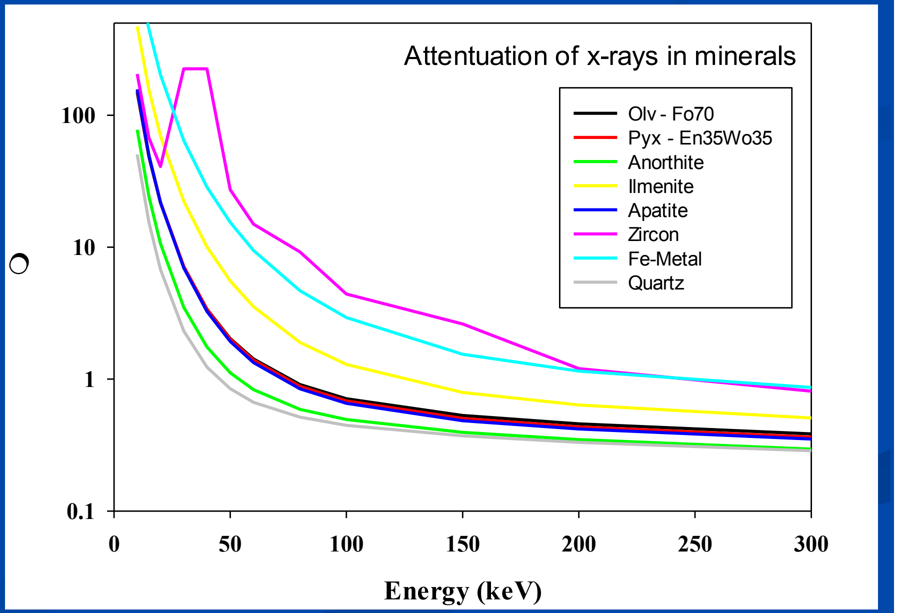


Relative brightness is caused by the density of the phase and average Z.



MuCalc tool - UTCT

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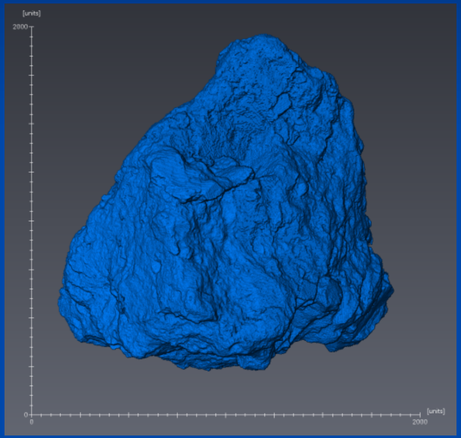
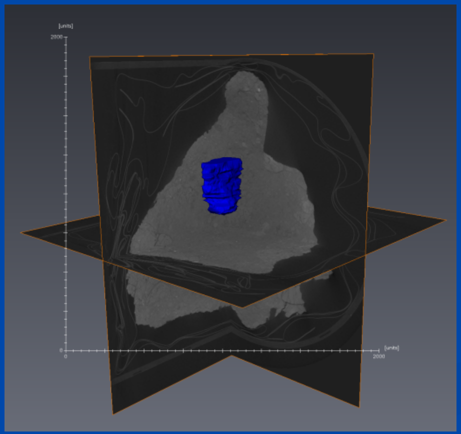
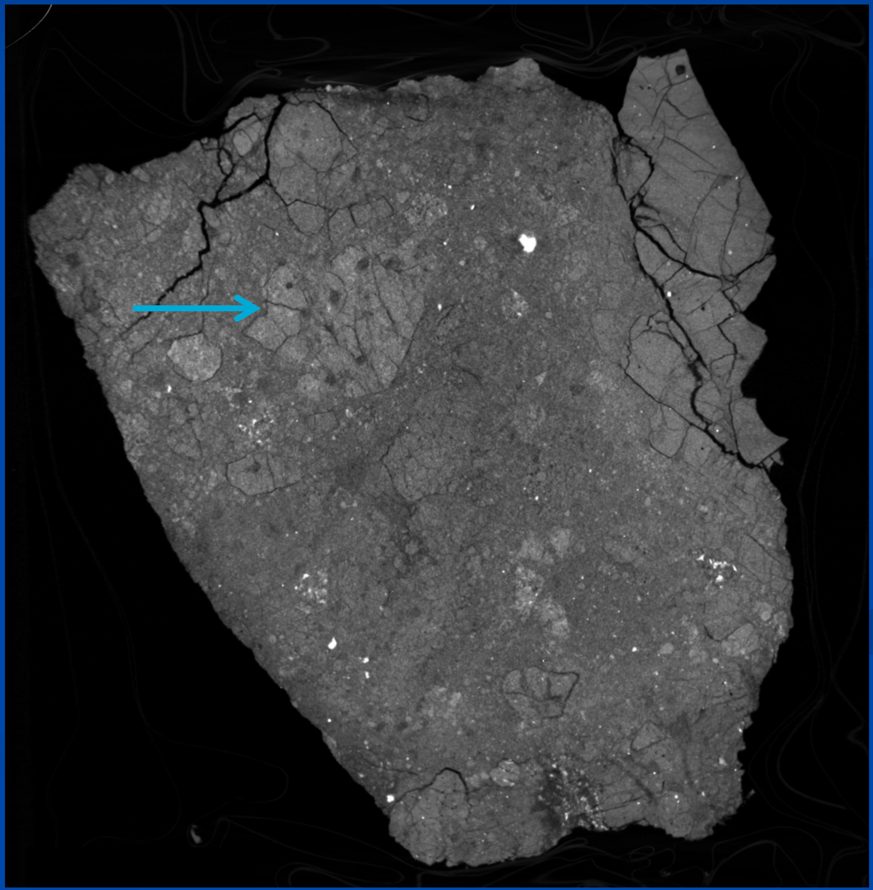


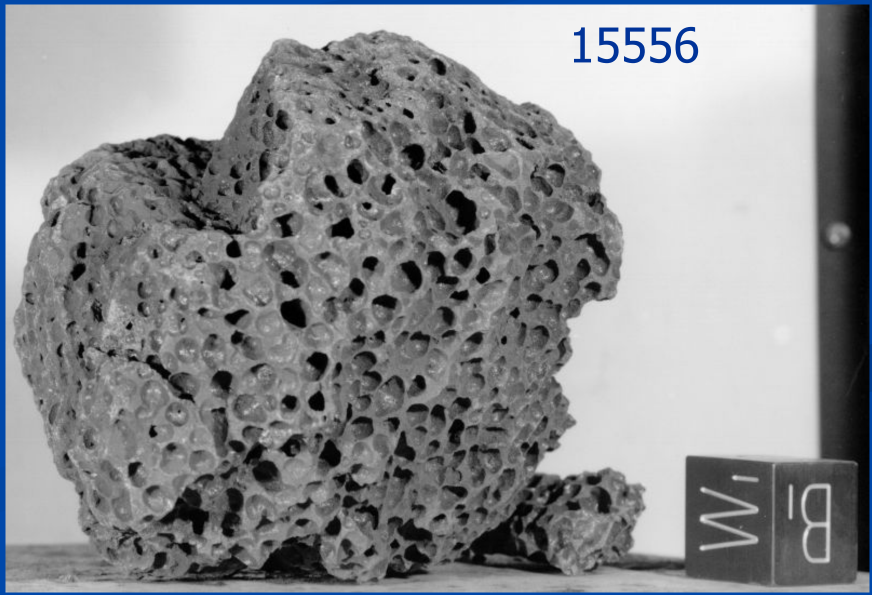


Clast = 0.637 cm3
Clast = ~1.9 g



Other lunar uses for micro-CT…

- In addition to clast identification, micro-CT scans would be useful to address a variety of other lunar sample questions.
  - Identification of mineral grains in igneous lunar samples.
  - Identification of zircons in lunar samples.
  - Measurement of macroscopic porosity in lunar samples



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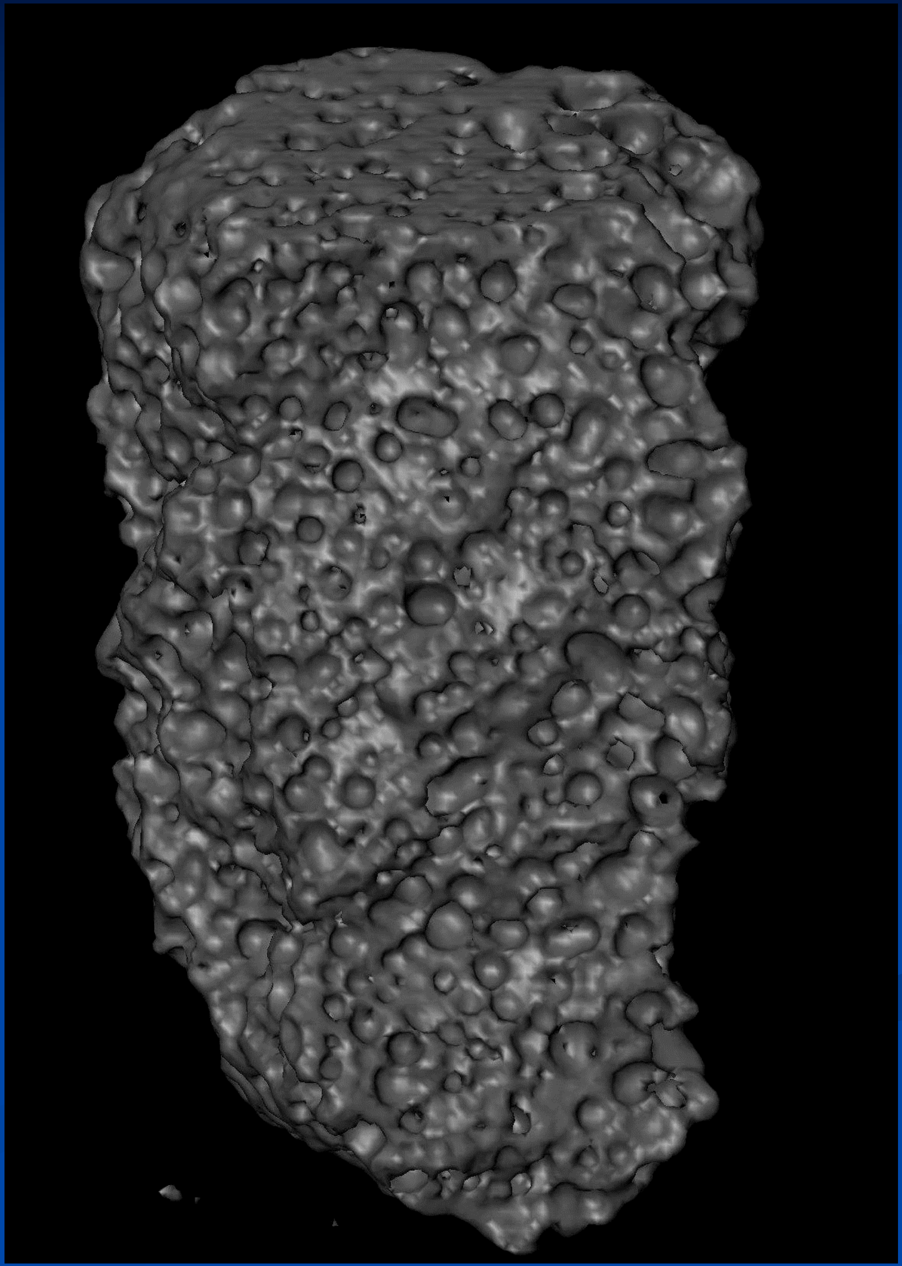
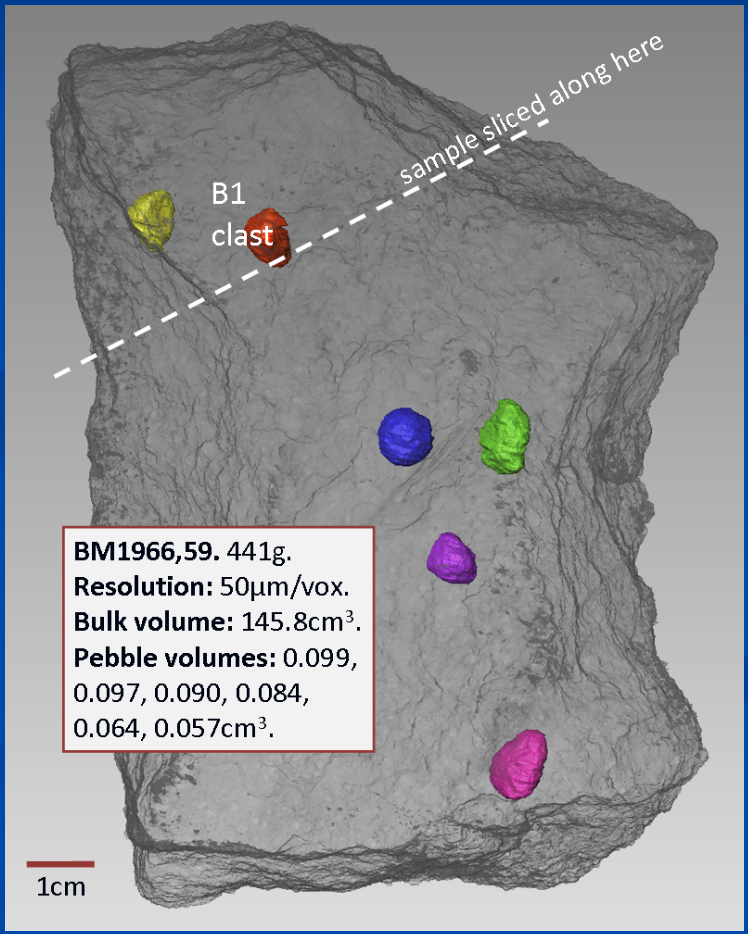
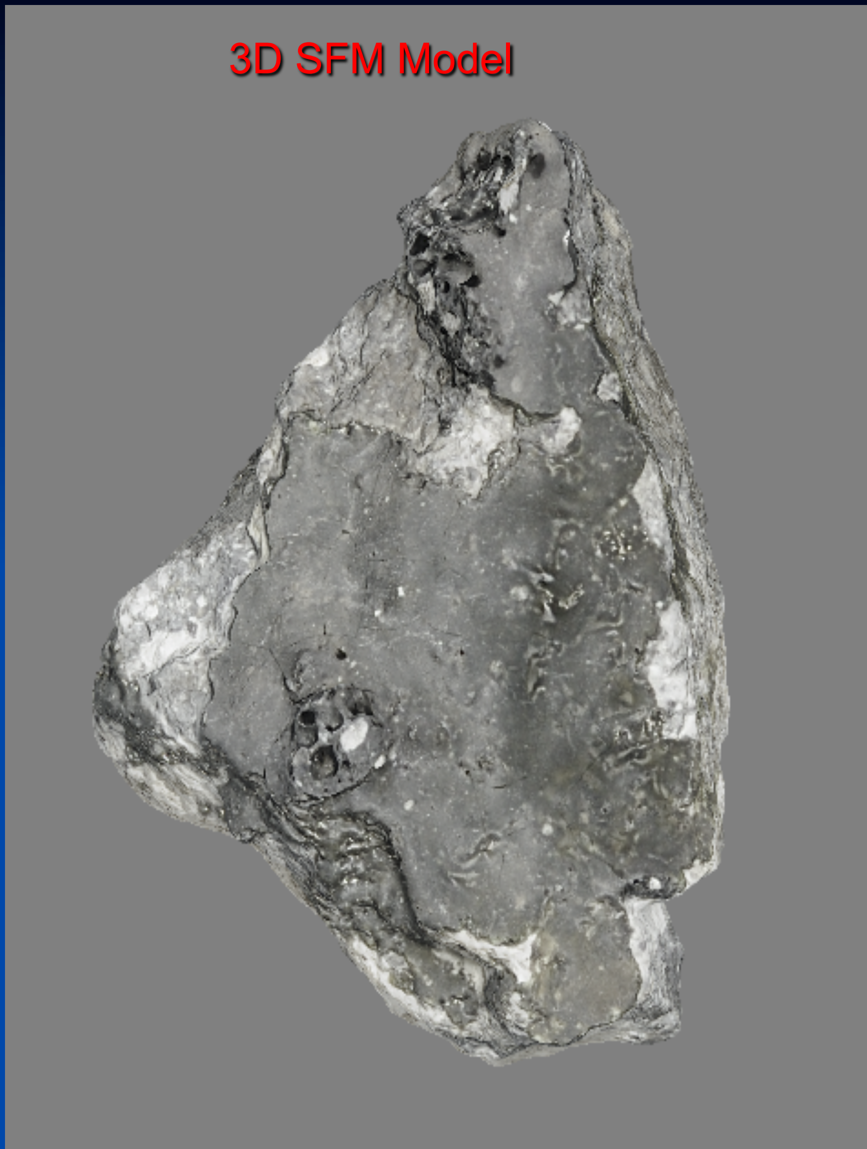
15556,215 – 12 cm tall, 354 g



Non lunar uses for micro-CT…

- Every single use I just highlighted for lunar samples applies to the Antarctic meteorite collections as well.
  - e.g., CAIs in chondrites, carbonaceous chondrite clasts in Howardites
  - Currently used by the NHM for all martian meteorite allocations.
  - Meteorite classification?
- Micro-CT will likely be a part of the basic curation plan for future lunar sample return missions; it is a base-level requirement for future Mars sample return; and it could be utilized for Osiris Rex.
- It would also be available to internal and external users for purely research purposes





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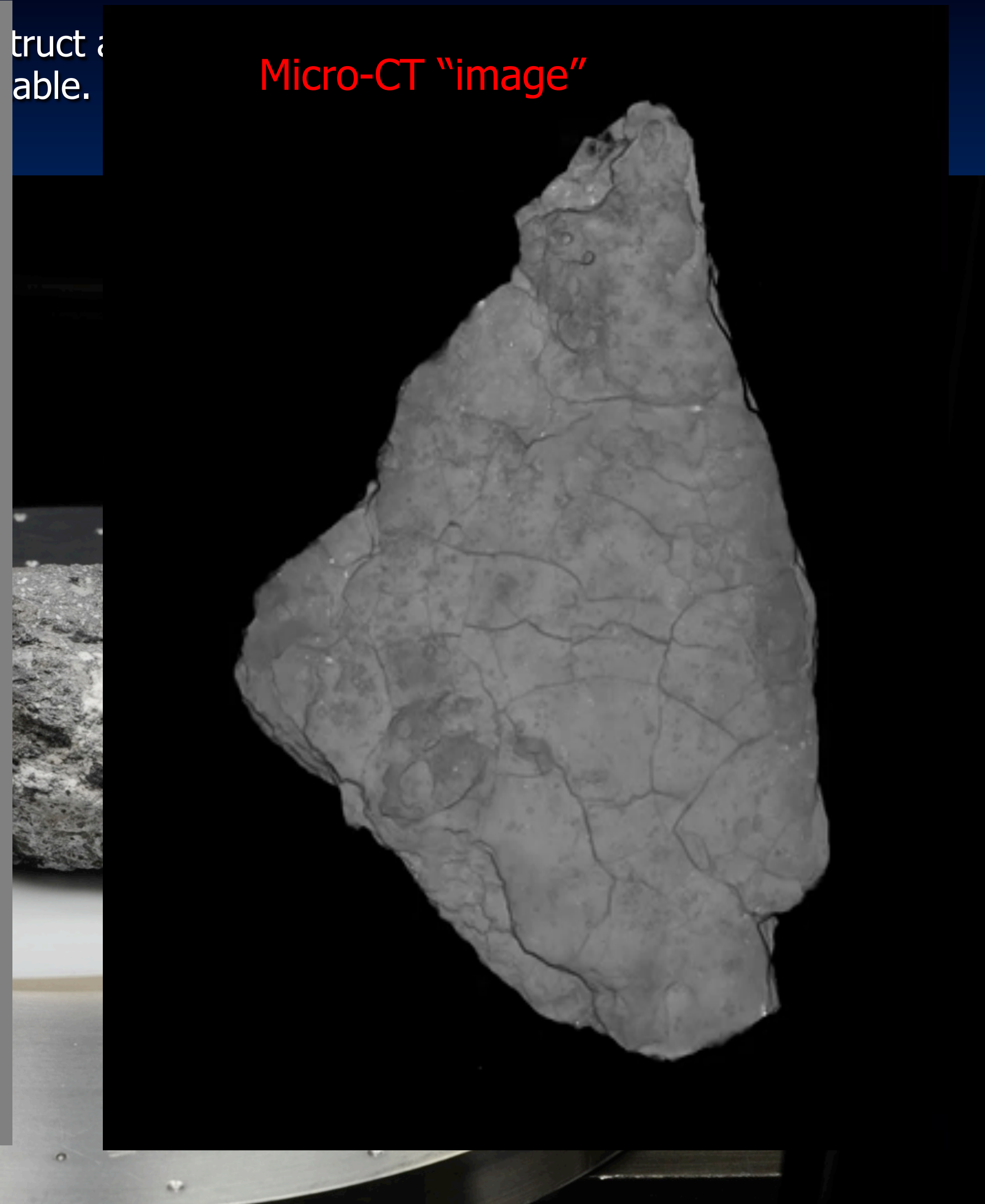
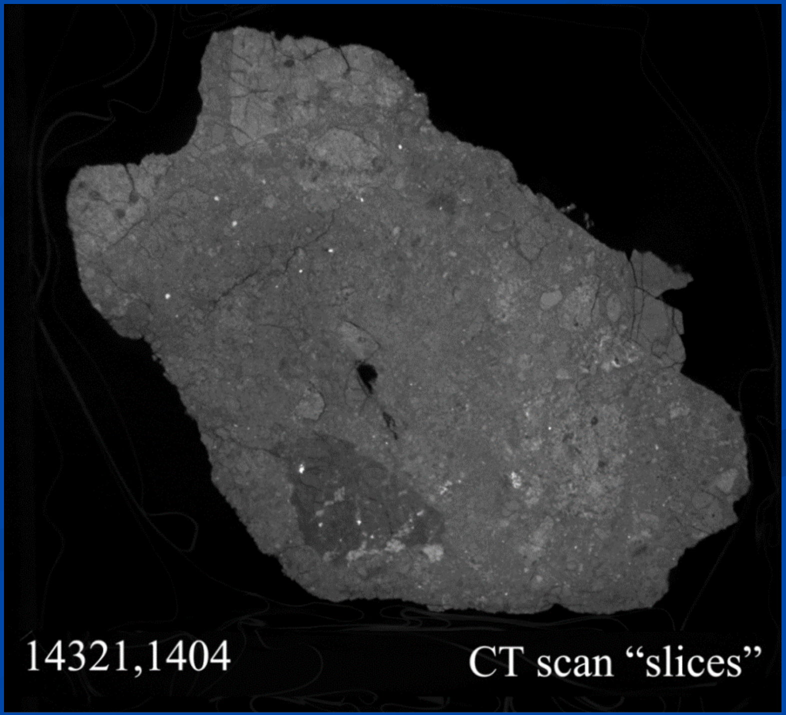
able.



Precision Photography Phase of Lunar Sample 60639 for SFM 3D Modeling. Photographs were taken in 15 degree increments totaling approximately 240 images.

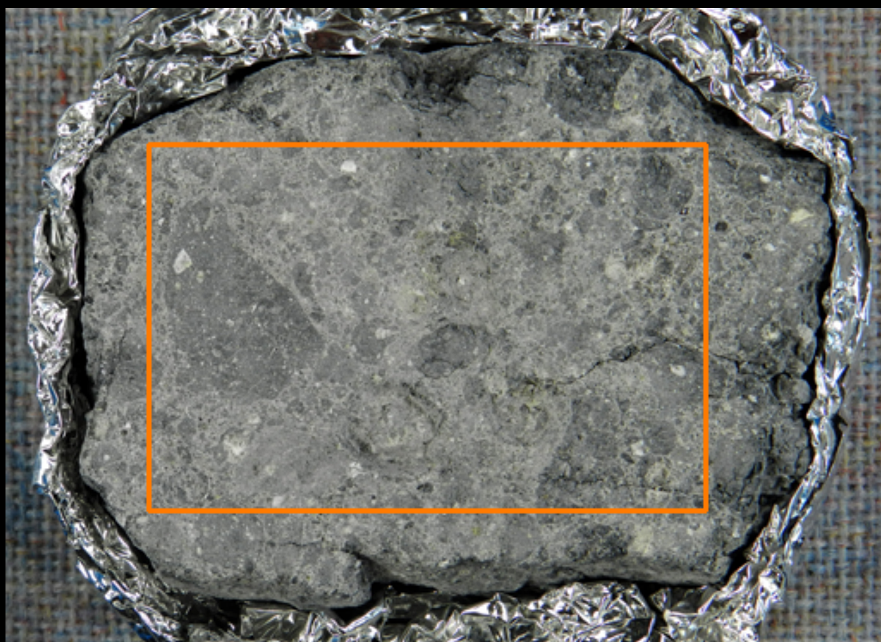
What would we do once we made the scans?

- A summary of the scan data would be "published" bi-annually to disseminate the information.
  - Similar to the ANSMET newsletter
- Individual slices and higher level data products (e.g., videos) would also be made available to the PIs for additional analysis.
- The scans would be used to identify the best places to make new band saw cuts, exposing the new clasts for more detailed study.
- These newly slabbed surfaces could be better characterized by micro-XRF



RGB = KAlSi

14305,483
Apollo 14 polymict breccia

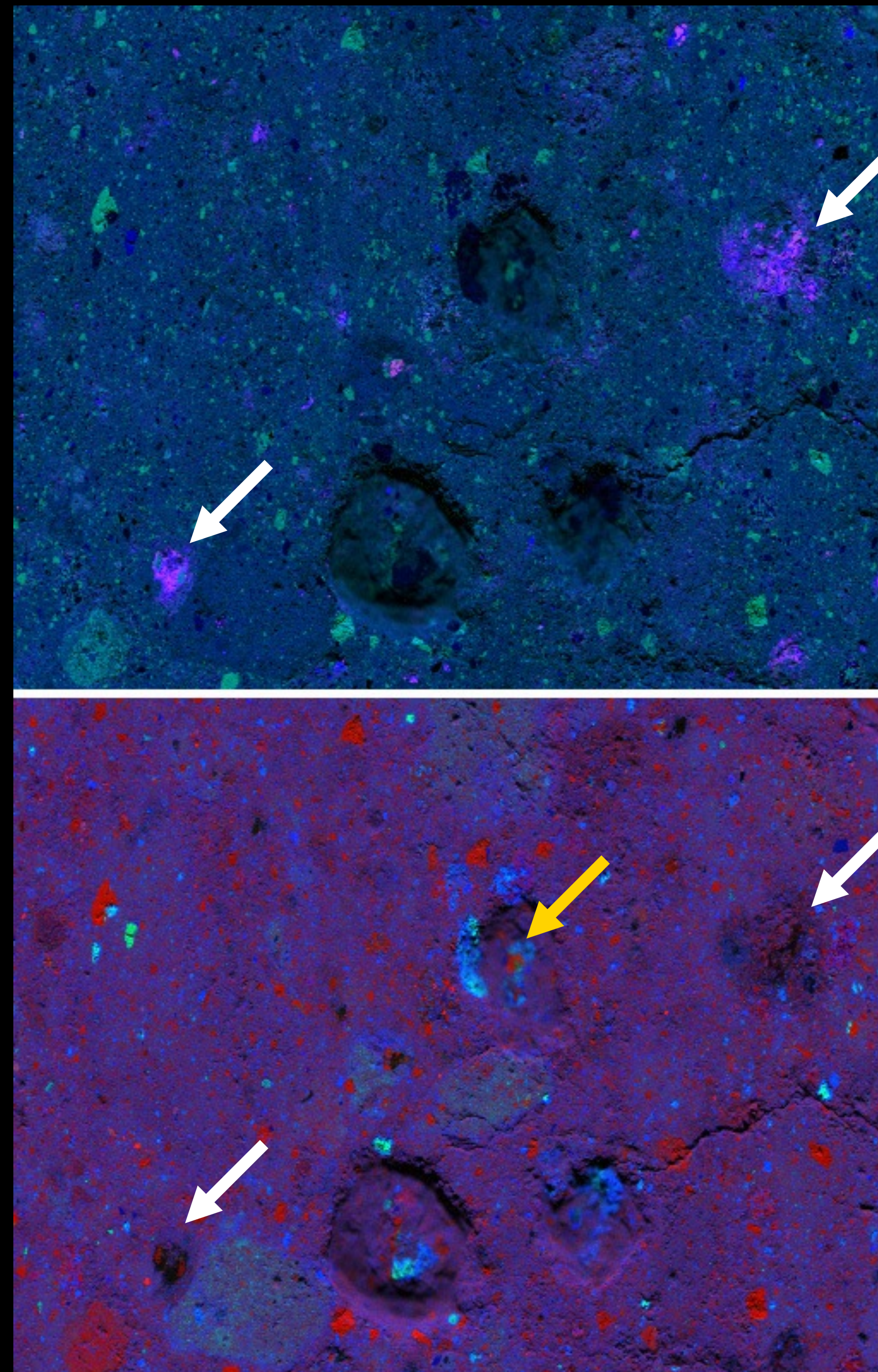


10 cm

Scans done on the EDAX Orbis PC
at Washington University

Micro-XRF scans at 40 kV, 800 μA, 30 μm beam

RGB = CaMgFe



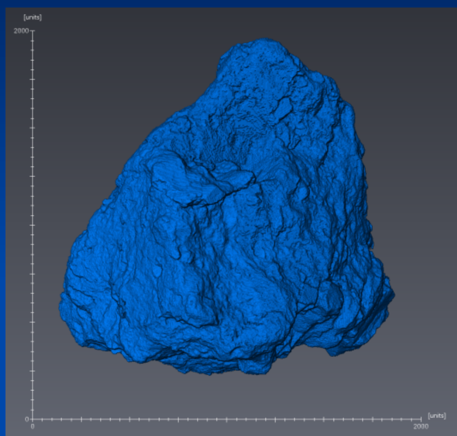
Bottom Line

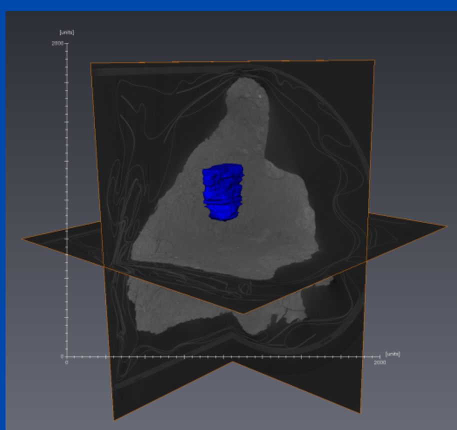
- Adding micro CT as a core part of the JSC curation capabilities will allow us to better utilize our existing collections – Conservation of Mass

- It will allow us to find "new" samples and provide better samples to scientists that allow them to address a wider range of scientific questions.

- At the same time, it will allow us to become proficient in a technique that is going to be important in many future sample return missions.

14321 video





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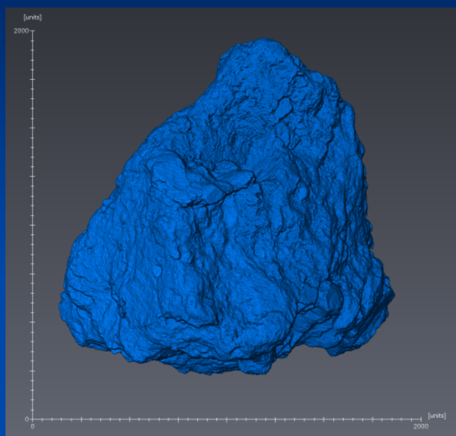

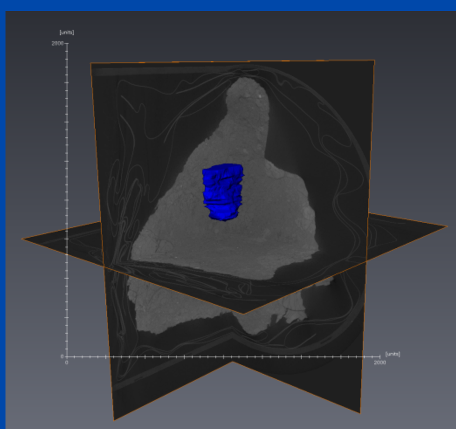

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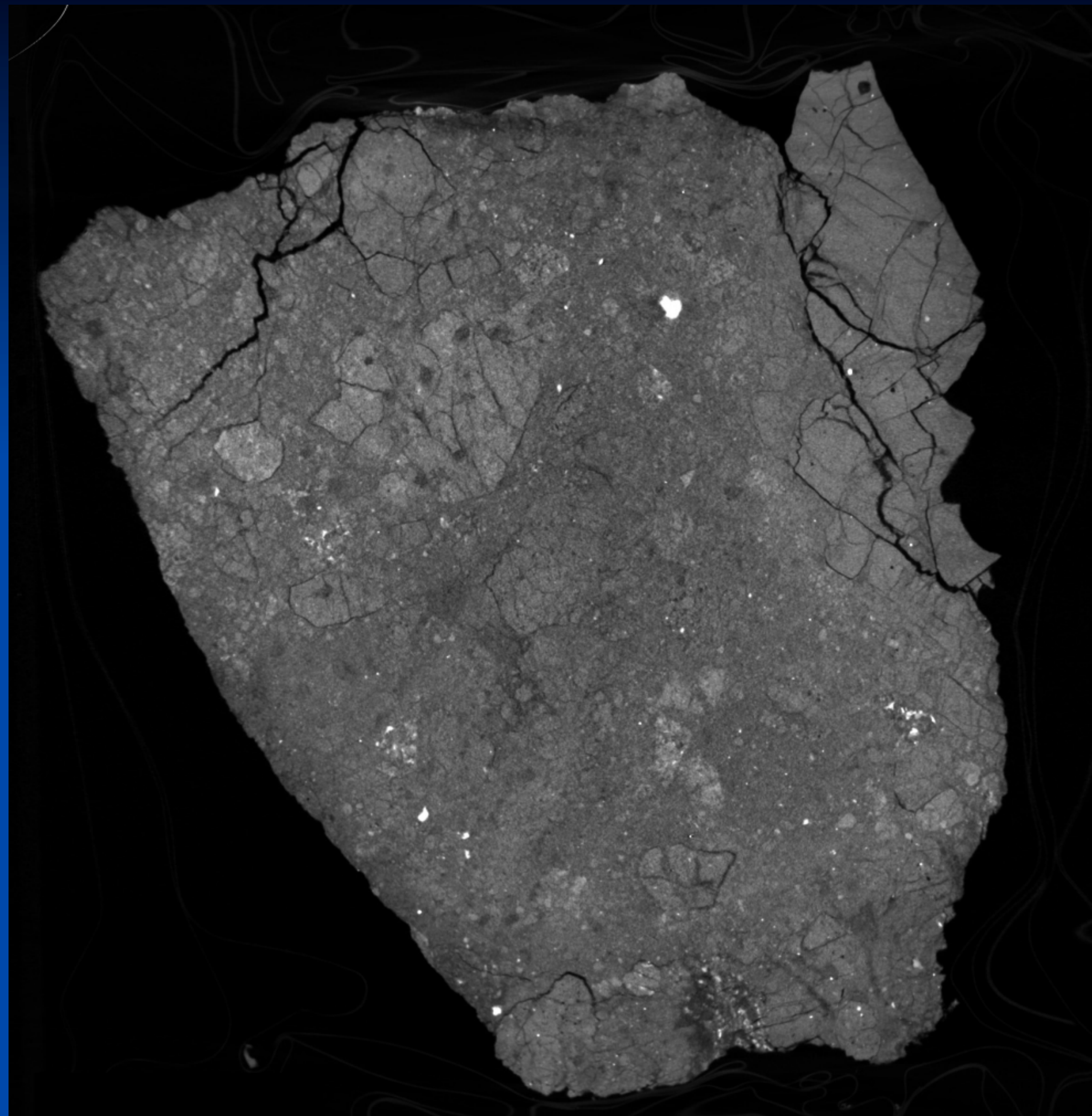
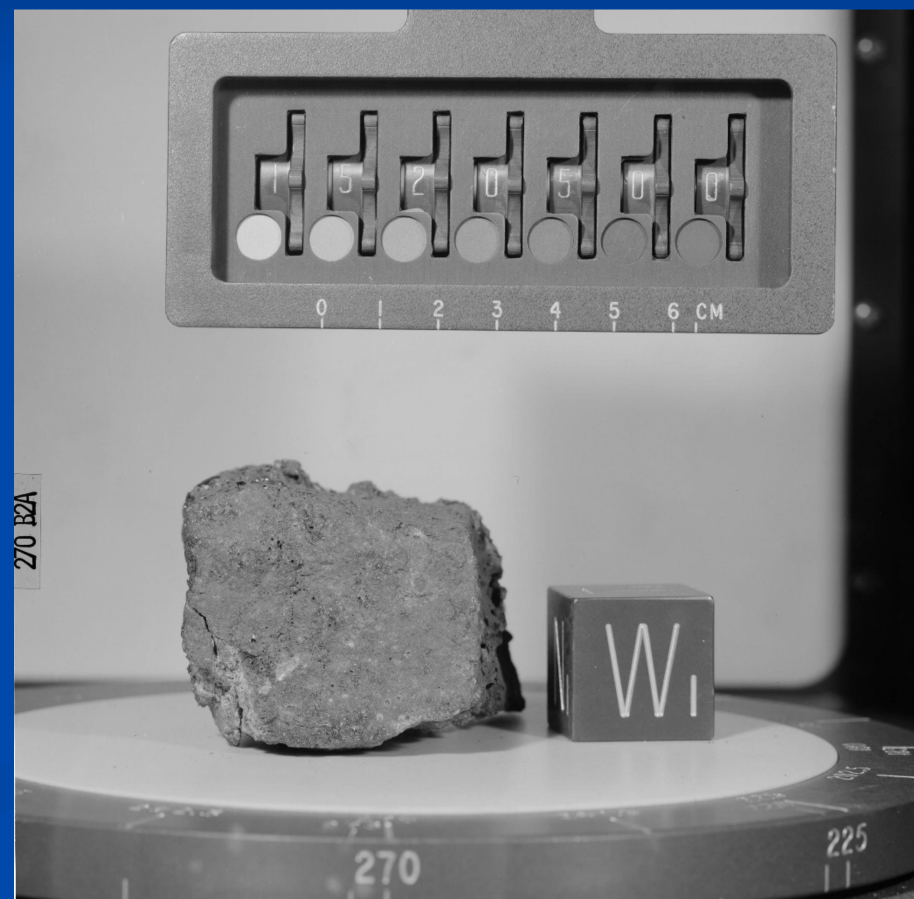


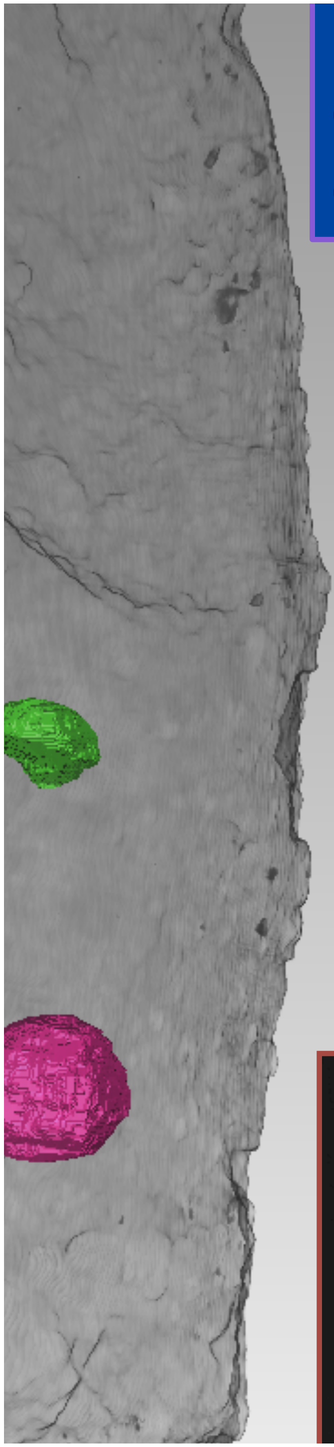
Scans of 15405 and 15205

- Pair of Apollo 15 regolith breccias, both of which have been shown to contain abundant evolved and/or KREEPy clasts, e.g., Granites, monzogabbro, etc.



Micro-CT for Curation

- While it's application to Apollo samples is new, using it on meteorites is not:
  - Numerous scientific studies, e.g., Kuebler et al 1999; Rubin et al 2001; McCoy et al. 2006; etc.
  - Becoming more common in the curation of meteorites, e.g., Smith et al. 2013; Hyde et al. 2013.
- CT imaging of large samples presents a unique set of challenges not necessarily applicable to previous research applications:
  - Resolution is tied to sample size.
  - Sensitivity is also tied to sample size.



Pebble volumes: 0.731, 0.190, 0.109, 0.040, 0.027cm^3.